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1 **Bringing cumulative technological culture beyond copying versus reasoning**

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13

14 **Abstract**

15 The dominant view of cumulative technological culture suggests that high-fidelity transmission
16 rests upon a high-fidelity copying ability, which allows individuals to reproduce the tool-use
17 actions performed by others without the need of understanding them (i.e., without causal
18 reasoning). The opposition between copying versus reasoning is well accepted but with little
19 supporting evidence. In this article, we investigate this distinction by examining the cognitive
20 science literature on tool use. Evidence indicates that the ability to reproduce others' tool-use
21 actions requires causal understanding, which questions the copying versus reasoning distinction
22 and the cognitive reality of the so-called copying ability. Our conclusion is that new insights
23 might be gained by considering causal understanding as a key driver of cumulative
24 technological culture.

25 **Keywords:** Cumulative Culture; Causal Understanding; Copying; Technical Reasoning; Social
26 Learning.

27

28 **On the cognitive origins of cumulative technological culture**

29 **Cumulative technological culture** (CTC) refers to the transmission of techniques or
30 tools over generations that is accompanied by an increase in their complexity and/or efficiency
31 [1–3] (see **Glossary**). The dominant view, called the cultural niche hypothesis [4,5], assumes
32 that CTC requires a **high-fidelity transmission** mechanism, with the rationale that **innovations**
33 are quickly lost if they cannot be faithfully transmitted to others. In this view, high-fidelity
34 transmission rests upon high-fidelity **copying** (also called imitation), which reflects the
35 cognitive ability to reproduce the actions performed by others with a high degree of fidelity
36 [6,7]. This copying mechanism is associated with a bias-based selection mechanism, which
37 orients the learner to the most appropriate models to be copied (e.g., prestige or conformity bias
38 [5]). The corollary is that “complex technologies such as bows result from the accumulation of
39 many, mostly small, often poorly understood improvements made across generations” (p. 1)
40 [8]. In some cases, the transmission can be accompanied by an understanding of how the tool
41 works, but **causal understanding** is not necessary for CTC [4,5,8,9]. Instead, it is the selective
42 transmission of occasional experiments and lucky errors that drives much of the evolution of
43 technology [10].

44 The cultural niche hypothesis has been mainly developed from evidence from
45 anthropology, economics, and biology. Yet, it is also a cognitive view of CTC given the marked
46 cognitive distinction drawn between high-fidelity copying and causal understanding.
47 Surprisingly, this view is relatively silent on the cognitive origins of these abilities, and
48 particularly on the copying ability (for a similar criticism, see [11]). For a cognitive scientist,
49 understanding how people copy the actions of others is not the end, but the beginning of the
50 story [12]. In this article, we investigate the cognitive science literature on **tool use** to examine
51 the concept of copying. The question raised here is whether the so-called concept of copying
52 possesses a cognitive reality in the domain of technical cognition and whether it can be easily

53 opposed to the concept of causal understanding. To answer this question, we will focus on the
54 literature on the use of physical tools (e.g., stone tool, bow, knife). Indeed, the study of how
55 modern humans use these tools offers a better proxy to understanding how technologies could
56 have been transmitted and improved during human evolution than more recent tools, which
57 require interfaces and arbitrary rules to work (e.g., washing machines, smartphones). In
58 addition, physical tools are commonly employed to make other tools. Thus, their use also
59 reflects another facet of CTC (i.e., tool making).

60 The idea that high-fidelity copying/imitation is crucial for cumulative culture is not
61 unique to the cultural niche hypothesis but widespread in the community ([13–15]; see also
62 [16]). The consequence is that less time has been devoted to the study of causal understanding
63 but the literature on this aspect is far from absent. For instance, archeologists have stressed that
64 early hominins [17–21] may have shown signs of causal understanding about stone fracturing
65 and knapping skills. Others have also argued that imitation is a good candidate for the cultural
66 inheritance of communicative gestures but not of technology [22]. In this vein, the present
67 discussion can contribute to building bridges between these different bodies of literature and
68 cognitive sciences with the aim of developing a specific framework on the role played by
69 technical cognition in CTC [23,24].

70 **The cultural niche hypothesis**

71 The cultural niche hypothesis argues that our technological adaptations mainly come from
72 “networks of diverse minds sharing information, lucky insights and chance recombinations in
73 cumulative fashion” (p. R383) [25]. This hypothesis rightly emphasizes that social learning is
74 a much more effective catalyst than asocial learning for individuals to acquire new information.
75 Elegant evidence demonstrates that collective intelligence is greater than the sum of individual
76 intelligence [26] and that it can be optimized with specific network dynamics ([27,28]; see also
77 [29,30]). We do not question these aspects. Instead, the question concerns the cognitive

78 processes at play when people acquire – or even improve – technical content. The cultural niche
79 hypothesis argues that “complex technologies can evolve without causal understanding” (p. 1)
80 [9], even if “in some cases elements of causal understanding may be passed along, but this is
81 not necessary” (p. 10923) [4]. This hypothesis has been supported by four main arguments.

- 82 • Partial-knowledge argument: Skilled tool makers can have no idea of whether alternative
83 designs would be better [4,9,25].
- 84 • Absence-of-increased-understanding argument: Experimental evidence indicates that the
85 improvement of a physical system over generations is not necessarily accompanied by an
86 increase of its understanding [8].
- 87 • Cultural-practices argument: There are many examples that suggest that humans often do
88 not understand why some cultural practices (mostly food practices) are effective (e.g., use
89 of chili peppers, cassava processing, Fijian taboos about some toxic marine species) [4,5].
- 90 • Serendipity argument: A great number of inventions and discoveries have resulted from
91 accidents or luck [31].

92 We will come back to each of these arguments at different times in the article, but our
93 discussion will concentrate on the cognitive reality of the copying versus causal understanding
94 distinction. If people can copy without understanding, then this implies that technical cognition
95 is supported by two distinct cognitive processes: Copying and causal understanding. The
96 question is whether the cognitive science literature on tool use supports this distinction.

97 **Causal understanding**

98 Causal understanding/reasoning serves two main functions: To predict events and to
99 control their occurrence ([32–34]; see also [35,36]). Causal reasoning refers to the ability to
100 reason about cause-effect relationships usually by deriving predictions for interventions
101 (“doing”) after learning by observing events (“seeing”) [37,38]. It is generally opposed to the
102 concept of **associative learning**. Causal reasoning possesses different forms in the human

103 brain. If you meet an unhappy friend, you can infer, from your knowledge of them, that the
104 cause of their unhappiness is the defeat of their preferred football team. In this case, you have
105 used your mentalizing skills, which involve a well-identified brain network (notably the dorso-
106 medial prefrontal cortex and the temporo-parietal junction [39]). If, however, you attempt to
107 understand why your knife cannot cut a piece of meat, you will use another form of causal
108 reasoning, directed to the physical object properties. This reasoning is called **technical**
109 **reasoning** and is associated with another brain network (notably the left inferior frontal gyrus
110 [IFG] and the area PF within the left inferior parietal lobe [IPL] [40]). We will hereafter use the
111 terms causal understanding and technical reasoning interchangeably because of our emphasis
112 on the technological dimension. The concept of technical reasoning has been supported by
113 evidence from experimental psychology, neuropsychology, and cognitive neuroscience (for
114 review, see [40,41]). Technical reasoning is not only causal but also analogical, allowing
115 individuals to transfer what is understood in one situation to another. It is based on **mechanical**
116 **knowledge** that is acquired through experience (i.e., **asocial learning** and **social learning** [42]),
117 and which refers to partial knowledge we have about how our physical environment works.
118 This knowledge is non-declarative and difficult to make explicit (just take a few moments to
119 think about a definition of “cutting”) and, therefore, differs from **semantic knowledge**. The
120 distinction between mechanical knowledge and semantic knowledge mirrors the distinction
121 repeatedly stressed in the archaeological and anthropological literature between knowledge and
122 know-how [43–46] or, more precisely, ideational know-how [43].

123 **Goal versus means**

124 When an individual observes another carrying out a tool-use action, two components of
125 the demonstration can be copied: The **motor action**, namely the body movement executed by
126 the model, or the **mechanical action**, namely the physical action that generally involves at least
127 two external objects (e.g., a hammer and a nail). In a way, the former can be viewed as the

128 means and the latter as the goal. The question is which of these components is preferentially
129 processed by an observer/learner. Many experimental psychology and cognitive neuroscience
130 studies have tackled this question by designing experiments in which each component is
131 manipulated independently. For instance, participants can have to “imitate” a model performing
132 a tool-use action while either the motor action or the mechanical action is congruent with the
133 participant’s tool-use action [47] or to judge the appropriateness of a model’s tool-use action
134 while the motor action is correct versus incorrect and/or the mechanical action is correct versus
135 incorrect [48–51]. The conclusions drawn from these studies are that (i.) it is easier to “imitate”
136 a model when the mechanical action is congruent, (ii.) the correctness of the mechanical action
137 has a larger impact on the judgment of what the model is doing than the correctness of the motor
138 action, and (iii.) the mechanical action is processed earlier than the motor action. These findings
139 suggest a goal-first effect in action observation, which has also been found when participants
140 merely scrutinize tools [52–54] or use tools in a non-action-observation condition [55,56]
141 including in stone-knapping contexts [57]. As a matter of fact, this effect is also generalizable
142 to non-tool-use actions (e.g., imitation of meaningless gestures [58]), confirming the early
143 intuition of Bernstein [59], a pioneer in motor-control field, who claimed that “one must
144 concentrate on the ‘what’ of the movement, the ‘hows’ come later by themselves” (p. 234; see
145 also [11]).

146 Neuroimaging studies have also helped us specify the neural network associated with the
147 observation of the mechanical actions performed by others. When someone observes another
148 individual carrying out an action directed toward an object (i.e., tool-use actions but also non-
149 tool-use actions such as grasping an object), a well-identified fronto-temporo-parietal network
150 is recruited, also known as the action observation network [39]. However, watching someone
151 else performing tool-use actions spontaneously engages an additional tool-use network that
152 includes the left IFG and the area PF within the left IPL [60] (**Figure 1A**). Importantly, this

153 tool-use network is specific to the processing of the mechanical actions performed by the model
154 and not to the processing of the model's intentions (i.e., the mentalizing network). This
155 mentalizing network can be engaged when participants are explicitly requested to think about
156 the reasons of 'why' the model is doing the tool-use actions [61], which confirms the existence
157 of different forms of causal reasoning in the human brain (see above).

158 **Do we copy the goals?**

159 Taken together, these findings indicate that people preferentially process the goal of a
160 demonstration and that this processing involves a specific tool-use brain network. Although
161 instructive, these findings do not rule out the idea of the so-called copying ability. After all, one
162 may consider that people simply encode and store (i.e., "copy") for future uses the information
163 associated with the mechanical action observed, without understanding the underlying causal
164 effects. If that were the case, then two distinct networks could be identified, one specialized in
165 the copying of mechanical actions with no associated understanding, another engaged when
166 people use tools in "asocial" conditions, such as when they solve mechanical problems by using
167 or making novel tools while no demonstration is provided or when they reason about physical
168 events. Such a finding would confirm the distinction drawn by the cultural niche hypothesis
169 between copying that is involved in social learning and the use of familiar tools versus causal
170 understanding that is involved in asocial learning and the use of novel tools/reasoning about
171 physical events. However, the cognitive science literature does not support this distinction.

172 It has long been observed that some left brain-damaged patients can suffer from tool-use
173 disorders, also called **apraxia of tool use** [62]. These patients can attempt to cut a piece of
174 bread with a spoon, to pound a nail by rubbing the hammer against the nail instead of
175 hammering with it, to put their glasses upside down, to try to power an electrical coffee machine
176 by plugging in a kettle as if the kettle was connected to the coffee machine, to try to brush their
177 hair with a toothbrush, or to shave their moustache by pressing strongly the razor against the

178 skin instead of making the expected shaving movements. Interestingly, there is a strong link in
179 these patients between the ability to use familiar tools and the ability to use or make novel tools
180 to solve mechanical problems [63–66] (for review, see [40]). Brain-lesion studies have
181 demonstrated that the difficulties in using both familiar and novel tools occur commonly after
182 damage to the tool-use network (notably the left area PF; **Figure 1B**). In other words, the same
183 brain network is recruited irrespective of whether the tools are familiar (presumably learned
184 through social transmission) or novel (presumably requiring asocial learning). This tool-use
185 network is activated when people focus on the appropriateness of mechanical actions involved
186 in tool-use actions [67,68] (**Figure 1A**), reason about physical events [69] (**Figure 1C**), or view
187 physical events without being explicitly asked to reason about them [69,70]. The cortical
188 thickness of the left area PF also predicts the performance on **psychotechnical tests**, in which
189 participants reason about physical events [71] (**Figure 1D**). This tool-use network therefore
190 supports our ability in “using, making, and reasoning about tools and more generally shaping
191 the physical world to our ends” (p. 29309) ([72]; see also [73]). Said differently, we do not only
192 copy mechanical actions, but we also attempt to understand them.

193 **Cumulative technological culture and technical reasoning**

194 Evidence that people do not simply “copy” others’ actions but use their technical-
195 reasoning skills to understand what they are doing also comes from the literature on CTC, and
196 particularly from **micro-society experiments** [74–76]. It has been repeatedly shown that
197 cumulative performance over generations can be observed in reverse-engineering conditions in
198 which participants can only scrutinize the predecessors’ product [8,77–79], even if the
199 progressive improvement is slower than in observation and teaching conditions in which
200 participants can interact together directly ([80]; for somewhat similar results, see [81]; see also
201 [13,18,82]). In reverse-engineering conditions, participants cannot copy because they cannot
202 see the mechanical actions performed by their predecessors. Therefore, technical-reasoning

203 skills are the best candidate to explain how people can gradually improve a physical system in
204 such conditions. As mentioned above, the left area PF is engaged in the observation of the
205 mechanical actions performed by others and evidence has demonstrated that its cortical
206 thickness predicts the performance on psychotechnical tests. Interestingly, the performance on
207 these tests has been found to be the best predictor of cumulative performance in micro-society
208 paradigms [83–85]. By contrast, creativity or **logical intelligence** scores do not predict
209 cumulative performance [83]. Initial experimental evidence has suggested that the
210 improvement of a physical system over generations is not necessarily accompanied by an
211 increase in its understanding [8] (the absence-of-increased-understanding argument). Partial
212 replications have nevertheless revealed the presence of a parallel improvement of the physical
213 system over generations and its understanding [78,86], not only when this understanding is
214 assessed with a test analogous to the system but also with a test in which the characteristics of
215 the system change (i.e., transfer test; for discussion on the link between analogical reasoning
216 and CTC, see [87]). In other words, these findings stress that it is the “abstract” understanding
217 of the physical system that improves over generations. It is noteworthy that, in micro-society
218 experiments in which participants have access to several models, the participants do not focus
219 only on the best one but screen a great number of them to obtain more accurate information
220 [88]. This spontaneous strategy, which is based on intervention (one of the two components of
221 causal reasoning, see above), is counterproductive if people simply copy the best model and
222 rather suggests that people seek to form a causal representation of how the physical system
223 works. It has also been reported that people do not explore randomly the space of solutions
224 ([8,89]; see also [90]). These findings indicate that people seek to enrich their causal
225 understanding by watching others, leading them to extract relevant and reject irrelevant
226 information. Finally, if the level of technical-reasoning skills plays a role in the ability to
227 reproduce and improve a technical solution over generations, it can be predicted that signs of

228 cumulative performance should be difficult to observe in children, who are supposed to possess
229 a lesser level of technical expertise. However, this level of technical expertise may be sufficient
230 to reproduce the technical solution of an adult model. A couple of experimental studies have
231 confirmed these predictions in reporting that young children can reproduce an adult model's
232 technical solution (even in a reverse-engineering condition) they could not reach just by
233 themselves [91] and show signs of cultural lineages in transmission chains but not of cumulative
234 performance [92].

235 **Can we copy without technical reasoning?**

236 As discussed so far, it appears difficult to consider that we learn technical content from
237 others without using our technical-reasoning skills. Another way of testing this hypothesis is to
238 see if individuals with technical-reasoning deficits (i.e., difficulties in using familiar tools or
239 solving mechanical problems by using or making novel tools) can recruit their copying skills
240 to solve technical problems. Two studies conducted by Goldenberg and colleagues [93,94]
241 provide an answer to this question. These studies included left brain-damaged patients with
242 tool-use disorders. Like most neurological patients, these patients had additional sensorimotor
243 or cognitive deficits (e.g., hemiplegia, aphasia), whose nature was heterogenous because it
244 depended on the location of lesions. It is known that these additional deficits do not provoke
245 apraxia of tool use. In other words, the difficulties faced by these patients in using tools reflected
246 the impairment of their technical-reasoning skills. They were trained to carry out simple
247 everyday tool-use activities, such as cutting a slice of bread and spreading margarine and jam
248 on it. For each activity, three distractors were also presented (e.g., a tin-opener) to make the
249 activity closer to the ecological/home context. The activities were trained for several weeks,
250 several days a week with specific sessions as well as for 20 to 40 minutes during the daily
251 sessions of occupational therapy. The training consisted of either errorless completion of the
252 whole activity (step-by-step demonstration; i.e., a kind of observational learning) or training of

253 details (i.e., directing patient's attention to the functional significance of critical features of the
254 actions; i.e., teaching). The results showed a post-therapy decrease of fatal errors (i.e., error that
255 made patients unable to proceed without help) and needs for assistance but not of reparable
256 errors (i.e., the error did not prevent the patient from continuing the activity). In other words,
257 although the patients committed fewer errors after the therapy, they still had difficulties to carry
258 out the activities and were not able to "copy" faithfully the tool-use actions. There was no
259 generalization of training effects from trained to non-trained activities and the rate of errors
260 increased when the trained activities were evaluated with a partially different set of tools (e.g.,
261 another knife). The success of training was preserved at follow up (6 to 30 months after the end
262 of the therapy) only in patients who had practiced the activity at home. In others, fatal errors
263 reappeared.

264 Two conclusions can be drawn from these results, which unfortunately stress the
265 difficulties of these patients to recover from their tool-use disorders. The first is that patients
266 with technical-reasoning deficits encounter severe difficulties in acquiring tool-use skills
267 through social learning (the model being here the occupational therapist). It is noteworthy that
268 these difficulties might reflect the more general inability to copy others' actions. This
269 possibility is not supported by neuropsychological and neuroimaging evidence, which has
270 indicated that tool-use skills versus imitation of gestures (symbolic and meaningless) involve
271 distinct neurocognitive processes [95,96]. The second is that, if we consider that the
272 improvement of performance over therapy, which was nevertheless prone to many errors,
273 reflects a potential copying ability, then this copying ability is characterized by a high learning
274 cost (several hours here for simple activities) and degrades if not frequently practiced. In
275 addition, this copying ability would be very sensitive to the lesser environmental changes (e.g.,
276 a new knife).

277 **Escaping from the copying versus reasoning distinction**

278 We conclude that the distinction between a high-fidelity copying mechanism and causal
279 understanding does not find support from the cognitive science literature on tool use. While
280 technical reasoning seems spontaneously engaged in social transmission of technical content
281 and critical for reproducing others' tool-use actions, an independent copying ability, if it exists
282 in the domain of technical cognition (**Box 1**), would not support faithful transmission and its
283 cognitive origins remain to be determined (**Figure 2, Key figure**). Put in more radical terms,
284 the copying versus reasoning distinction may be a red-herring because high-fidelity
285 transmission of technical content is driven only by technical-reasoning skills.

286 In our opinion, the literature suggests that participants use their technical-reasoning skills
287 to develop their own causal understanding of the situation and use this understanding to solve
288 technical problems. We are born with limited causal understanding of physical principles (e.g.,
289 support) and that understanding evolves during infancy and adulthood through experience [97–
290 99]. Asocial (or individual) learning and social learning are two ways of acquiring experience
291 and enriching our understanding and they provide complementary information, with social
292 learning guiding learners towards more effective solutions and asocial learning allowing
293 individuals to adapt that knowledge to their own constraints and goals. Inter-individual
294 variability in terms of causal understanding/technical-reasoning skills can explain the presence
295 or absence of high-fidelity transmission. High-fidelity transmission is a mechanism that
296 involves both the information sent by the model and the learner's ability to process it. This
297 transmission can be disrupted if some information is incompletely sent and/or if the learner
298 cannot process appropriately the information received. The more advanced the causal
299 understanding of the problem is, the more individuals can transmit, acquire, and maintain the
300 technical behavior over time. This may lead to faithful transmission, when the technique is
301 optimal and causal understanding is easily accessible, but it can also lead to improvement over

302 time (e.g., technique suboptimal and understanding is easily accessible), adaptation to one's
303 own needs, divergence through the use of a completely different solution, or the loss of
304 technical knowledge (e.g., when the understanding is advanced and difficult to acquire).

305 Considering that causal understanding can drive CTC does not mean that individuals must
306 have a perfect causal representation of physical events since we necessarily only possess a
307 partial causal understanding of a technique (**Box 2**). The question is one of degree: What is the
308 degree of understanding necessary to sustain cultural transmission? Interestingly, our view
309 predicts that the loss of technical knowledge along cultural transmission chains is not
310 irreversible because participants with higher technical reasoning abilities and/or more elaborate
311 causal understanding can reconstruct the technical knowledge that has been lost [86]. In other
312 words, the phenomenon of high-fidelity transmission does not necessarily need to have a strict
313 correspondence at the individual level but could be supported by a reconstruction process
314 [6,100–102] implemented through technical reasoning. New population-based experiments,
315 computational modelling, and empirical research are needed to provide support for these
316 cultural dynamics.

317 **Concluding remarks**

318 The cultural niche hypothesis claims that CTC is driven by both copying and selection
319 mechanisms and minimizes the role played by causal understanding. The cognitive science
320 literature depicts a different scenario, in which the degree of understanding might explain the
321 quality of the transmission, thereby reintroducing the role played by individual cognition in
322 CTC and more generally cultural evolution (see [103,104]), a view compatible with the cultural
323 attraction theory [100,105,106]. More broadly, our discussion also leads us to revisit the
324 classical high-fidelity transmission versus innovation distinction (for discussion on the
325 innovation component, see [107]). If we envisage that technical reasoning plays an active role
326 in the transmission, we can also envisage that it is also engaged in innovation, by supporting

327 the recombination process that characterizes most of innovations [31,108]. Even if some
328 innovations result from ‘lucky errors’, “the inventor also [has] a mind prepared to recognize
329 the discovery embedded in chance observation” (p. 5) [31]. Future research could be envisaged
330 to examine whether people with better understanding are more prone to detect these lucky errors
331 or perform recombination (the serendipity argument; see **Outstanding questions**). If such
332 findings were obtained, then this could lead to an extended scenario in which causal
333 understanding in concert with asocial and social learning drives both the transmission and
334 innovation components of CTC [109].

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- 567

568 **Box 1. Not one but several cumulative cultures with different cognitive origins?**

569 Current evidence suggests that cumulative culture is not a unified phenomenon but might
570 recruit a collection of domain-general [110–113] and domain-specific [22] cognitive
571 mechanisms. Accordingly, the question “is causal understanding necessary for cumulative
572 culture?” makes little sense without specifying the domain of interest. For instance, the fact that
573 people can follow some cultural (mostly food) practices without understanding why they are
574 effective has been repeatedly used to support the cultural niche hypothesis (the cultural-
575 practices argument) [4,5]. We do not dispute this evidence. Food processing needs to retrieve
576 information about each recipe specifically (e.g., ingredients, steps, step order and duration) that
577 is stored in semantic memory, which refers to knowledge about facts, concepts, people, or social
578 usages [114]. This memory, which is supported by ventral brain regions, notably the temporal
579 cortex [115], is not involved in the technical dimension of tool-use skills. Thus, patients with
580 selective semantic-memory deficits do not meet difficulties in solving mechanical problems
581 with novel tools but can be unable to name or describe the function of familiar tools they can
582 nevertheless use appropriately [116–119]. Importantly, contrary to technical skills, no evidence
583 indicates that semantic knowledge needs causal understanding to be acquired. We can know
584 that Saturn is a planet, dinosaurs existed million years ago, or cassava roots are commonly
585 soaked in water for several days before eating them, without any causal understanding about
586 how this knowledge was built. Note however that food practices are based on at least two
587 cognitive components. The first is linked to semantic memory. The second is the technical-
588 reasoning component because food processing requires tools (e.g., knives, plates) and
589 techniques (e.g., fire making, cutting), which constitute a repertoire that people can exploit for
590 different recipes. Using these tools and techniques involves technical reasoning and, therefore,
591 causal understanding. The consequence is that the cultural evolution of food processing is
592 linked to causal understanding, even if it plays an indirect role. The same is true for many

593 cultural domains because cultural evolution in one domain (e.g., arts [120]) is often intertwined
594 with cultural evolution in other domains ([121]; see also [122]). This technical-reasoning versus
595 semantic-memory distinction provides one potential avenue to explain why part of cumulative
596 culture can be passed along through high-fidelity copying and without understanding, whereas
597 other parts require causal understanding.
598

599 **Box 2. Causal understanding is necessarily partial**

600 Causal understanding refers to the ability to predict the effects of intentional
601 modifications of a system and is necessarily partial. For instance, if you ask ten renowned
602 engineering scientists specialized on archery mechanics to predict the effects of modifying the
603 shape of present-day bows (**Figure IA**), you may observe that their predictions (i.e., noise
604 reduction, arrow speed) are almost perfect, generating the illusion of complete causal
605 understanding. Imagine now that a time travel machine transports them to the future (say 3500
606 AD), in which bows have remarkable shapes and are made of new materials (**Figure IB**). You
607 question the ten scientists on these futuristic bows and notice that they meet difficulties in
608 predicting the effects of modifications. You conclude that, after all, their causal understanding
609 is not complete but partial as they cannot predict the effects of all the modifications. This
610 conclusion is trivial because our causal understanding does not allow us to foresee all the effects
611 that can occur in the physical world (for a somewhat similar discussion about the manufacture
612 of Samurai swords, see [87]). Although indisputable, the partial knowledge argument has been
613 repeatedly employed by the proponents of the cultural niche hypothesis to support the idea that
614 causal understanding is not necessary for CTC [4,5,9]. For instance, Harris et al. [9] interviewed
615 skilled Hazda bowyers and compared their bow-making beliefs to those revealed by
616 engineering research. They found that Hazda bowyers were better than chance on 7 of 13
617 questions but nevertheless concluded that “expert-level causal understanding isn’t necessary
618 for cumulative culture in extant humans” (p. 5) [9]. We cannot expect Hazda bowyers to have
619 perfect and complete bow-making knowledge, who would have such knowledge? A basic
620 assumption in psychometrics is to consider the measure as relative and not absolute.
621 Psychologists do not compare individuals’ performance on vocabulary tests with dictionary
622 entries or academicians’ vocabulary because the risk is to generate floor effects with
623 performance far below the “absolute” expert level. It is more revealing to compare an

624 individual's performance relatively to a norm/control group to apprehend, all else being equal,
625 what is specific to the individual studied. Harris et al. [9] did not use such a control group but
626 if their purpose was to show that causal understanding is not necessary for CTC, it would have
627 been more interesting to report that Hazda bowyers do not outperform a control group (e.g.,
628 Hazda non-bowyers) on a bow-making understanding test.
629

630 **Figure Legends**

631 **Figure 1. Neurocognitive bases of technical reasoning.** **a.** Neuroimaging studies have revealed a brain network
632 specific to tool-use action understanding [67] and observation [60]. This network is left-lateralized and includes
633 the area PF within the inferior parietal lobe and the inferior frontal gyrus. The cognitive processes associated to
634 these areas need to be specified. **b.** Brain-lesions studies have found that familiar and novel tool use/making is
635 systematically impaired after damage to the left area PF (Green: Novel tool use; Other colors: Familiar tool use
636 [65,123–126]), stressing the critical role of this area in the ability to reason about mechanical actions during tool
637 use. **c.** Neuroimaging evidence also indicates that the left area PF, along with bilateral premotor cortex and superior
638 parietal lobes, is recruited when people reason about physical events (i.e., physical task or physical interactions)
639 compared to non-physical events (i.e., color task or social interactions) [69]. **d.** The involvement of the left area
640 PF in understanding about physical events was also confirmed by a specific link between the cortical thickness of
641 the left area PF and performance on a psychotechnical test [71].

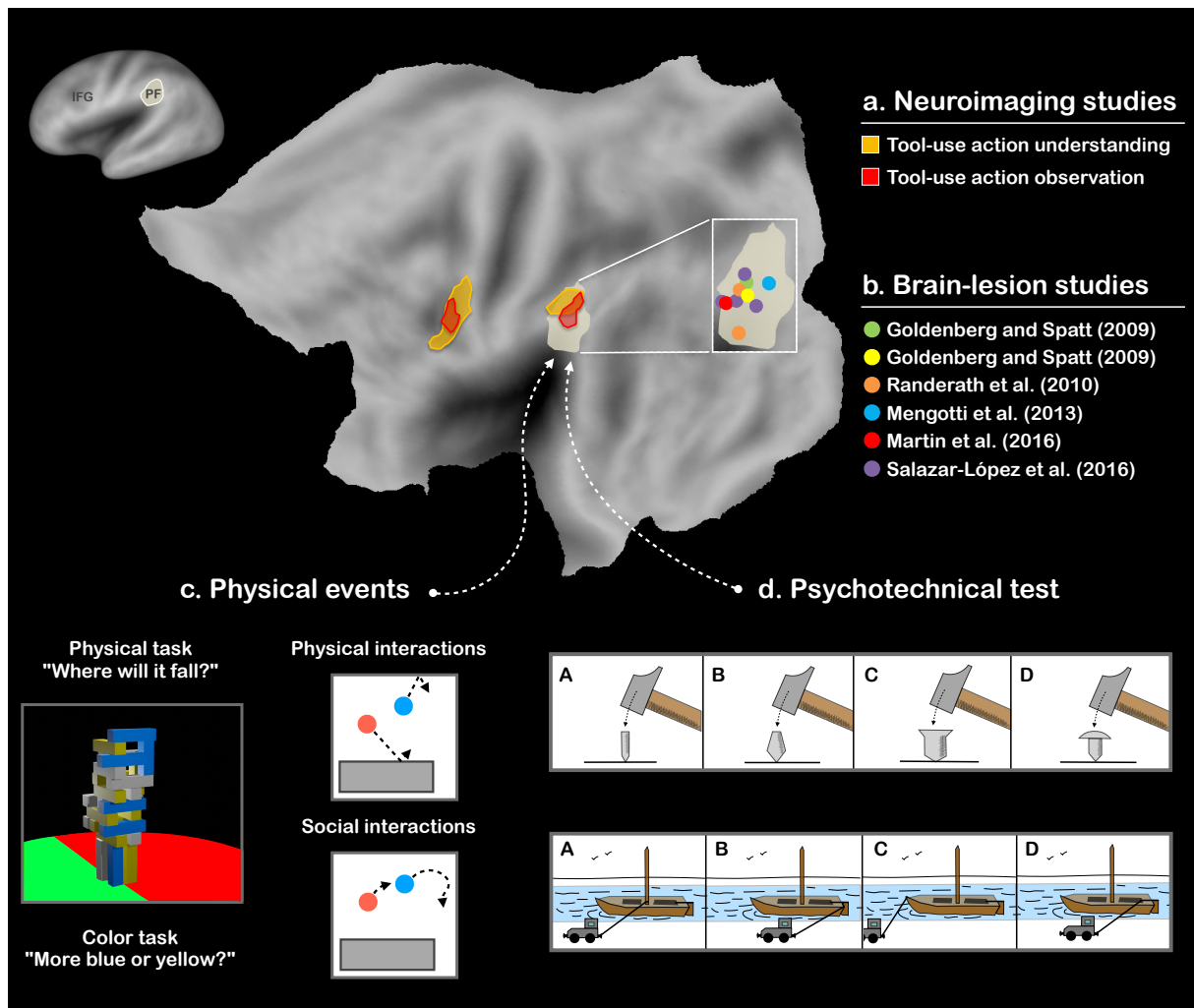
642 **Figure 2 (Key figure). Causal understanding and high-fidelity transmission.** The technical-reasoning
643 hypothesis (**a**) assumes that causal understanding is spontaneously engaged in social transmission of technical
644 content and critical for reproducing and improving upon others' tool-use actions and technologies. Thus, the
645 phenomenon of high-fidelity transmission does not necessarily need to have a strict correspondence at the
646 individual level but can be supported by a reconstruction process implemented through causal understanding,
647 which can be particularly useful when the technical content transmitted is degraded or incomplete (e.g., accidental
648 modification [86]). This hypothesis does not exclude the potential role of memory (i.e., working memory and
649 episodic memory) to store the information transmitted and/or reconstructed over the individual's lifetime.
650 However, the technical behavior can be maintained only if the individual understands it. This is consistent with
651 evidence indicating that children reproduce both the relevant and irrelevant actions performed by a model in the
652 short term (immediately after the demonstration) but only the relevant actions in the long term (after a delay of
653 one week) [127]. Without causal understanding (**b**), the information is progressively lost in the long term,
654 suggesting that high-fidelity transmission can take place only if the technical content is quickly transmitted
655 between individuals (i.e., in the short term) and without the presence of accidental modifications.

656 **Figure I. Present-day (Reflex-deflex) and futuristic (3500 AD) bow designs.**

657

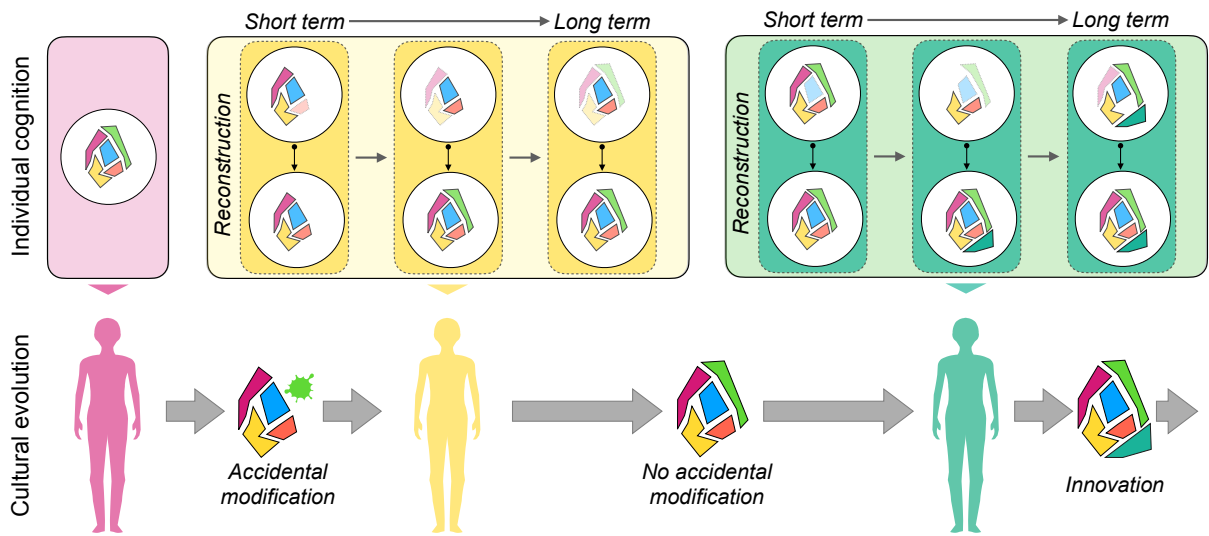
Glossary

Term	Definition
Apraxia of tool use/tool-use disorder	Inability to select appropriate familiar tools for a given tool-use action or to perform effective mechanical actions even when suitable familiar tools and objects are provided. This disorder appears after brain damage.
Asocial learning	Learning that does not result from the observation of, or interaction with, another conspecific or its product.
Associative learning	Ability to learn associations between passively observed events (i.e., classical conditioning) or between interventions and outcomes (i.e., operant conditioning). Associative learning involves representations about proximal relations (i.e., observable events).
Causal understanding/reasoning	Ability to infer causal structure by observing the patterns of conditional probabilities among events, by examining the consequences of interventions or, usually, by combining the two. Causal reasoning involves representations about distal relations (i.e., unobservable entities; e.g., physical forces). Causal reasoning possesses multiple forms in the human brain depending on the domain (e.g., social, physical). Here, we use the terms causal reasoning and technical reasoning as synonyms because of our focus on the role of causal reasoning in the technological domain.
Copying/imitation	Ability to copy a technical behavior with a high degree of fidelity (also called propensity fidelity). In the literature, the term copying, and more specifically the term imitation, does not imply the absence of causal understanding. Here, we will refer to the conception proposed by the cultural niche hypothesis, according to which copying does not require causal understanding, which justifies the distinction between these two cognitive abilities.
Cumulative technological culture	Accumulation of socially learned technical content over generations, allowing humans to develop tools/technologies that are too complex to have been invented by a single individual.
High-fidelity transmission	Transmission of information between a model and a learner with a relatively high degree of fidelity (also called episodic fidelity). This describes the whole process, which involves both the information sent from the model and the learner's ability to process this information.
Innovation	Production of a new technology either through novel invention, modification, or recombination.
Logical intelligence	Logical intelligence encompasses different forms of reasoning (e.g., induction) that apply to relations that are not necessarily causal (e.g., taxonomic relations; lions have property X, mammals have property X).
Mechanical action	Interaction between physical objects (e.g., a hammer pounding a nail).
Mechanical/technical knowledge	Nondeclarative knowledge about physical principles that is acquired through experience. This knowledge is necessarily partial.
Micro-society experiment	Experiment in which participants must improve a physical system collectively through the social transmission of technical content. The transmission can be indirect (i.e., reverse engineering; only the product is transmitted) or direct (i.e., observation, teaching). The definition proposed here focuses on the technological dimension, but micro-society experiments can also be conducted in other domains such as language.
Motor action	Movements executed by an individual. These movements can be involved in tool-use actions or not (e.g., grasping an object to move it).
Psychotechnical test	Test that assesses individuals' understanding of physical events.
Semantic knowledge	Declarative knowledge about facts, concepts, people, or social usages.
Social learning	Learning that is influenced by observation of, or interaction with, another conspecific or its product.
Technical reasoning	Ability to reason about the physical world. This reasoning is both causal and analogical.
Tool use	Use of any handheld physical implement that is used to make changes in the environment.

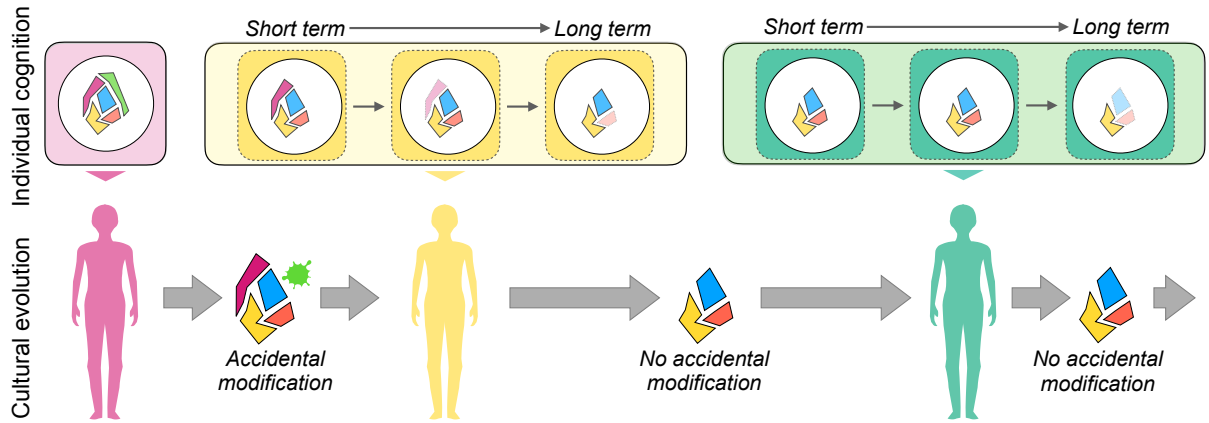


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661

a. With causal understanding

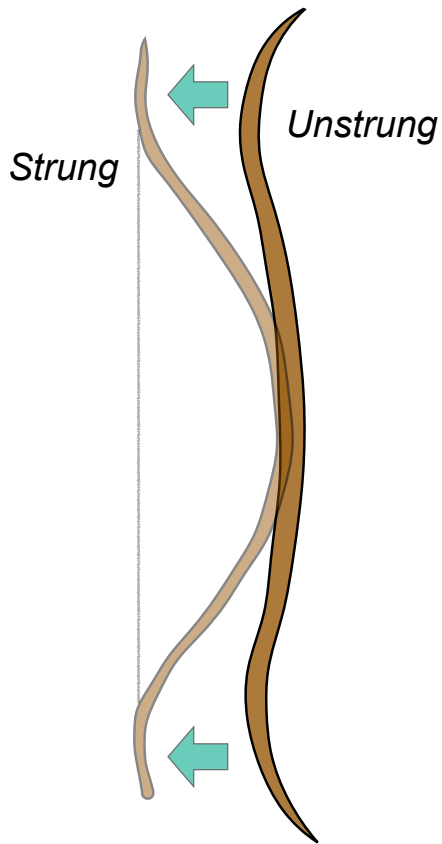


b. Without causal understanding



662
663

a. Present-day design



b. Futuristic design

